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Magnetic Design of Small-Aperture Dipoles of the Shell and Block Type

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Abstract:

This note collects viewgraphs from a talk presented at the workshop "Magnets for a Very Large Hadron Collider" held at Port Jefferson in November 1998. The workshop was organized by the Magnet Technologies Working Group, appointed by the Steering Committee for a Very Large Hadron Collider. Goal of the workshop was to develop innovative concepts in magnet design and fabrication, that would result in significant cost reductions. In particular, the present study is devoted at exploring the magnetic performance of small-aperture dipoles. After some general considerations on the choice of the optimal design field as function of aperture and conductor parameters, two designs are presented, one of the shell type and one of the block type. In both cases, the design parameters are 30 mm aperture and 12-13 T short sample field (assuming a current density of 2-3 kA/mm^2 at 12 T and 4.2 K). The two designs are compared between them and with a 50 mm aperture design of comparable performance, which is being developed by a collaboration involving Fermilab, LBL and KEK. It is found that, for these parameters, the 30 mm aperture magnet allows substantial savings in superconductor with respect to the 50 mm case, and that the shell and block designs are substantially equivalent in terms of conductor efficiency and field quality. A comparison of vertical vs. horizontal layout of the two apertures in a two-in-one magnet of the block type is also carried out. It is found that the vertical layout, which present interesting features from the fabrication standpoint, requires substantially larger yoke in order to achieve the same tranfer function.

Magnetic design of small-aperture dipoles of the shell and block type

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- Choice of design parameters
- Shell vs. Block type design:
  - conductor efficiency
  - field quality
- Two-in-one: yoke diameter requirement for horizontal vs. vertical layout
- Conclusions

Aperture requirement

SSC: 40 → 50 mm LHC: 50 → 56 mm

VLHC: 50 → 30 mm?

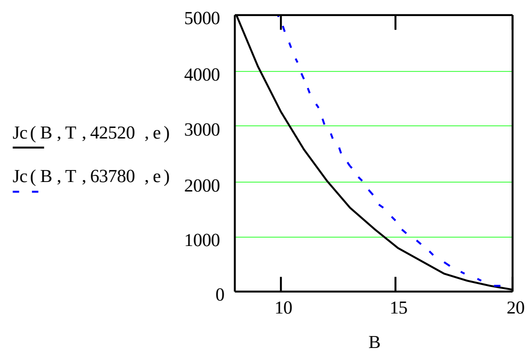
Charge: Guided by the snowmass '96 parameter set, explore and develop innovative concepts that will result in significant cost reductions.

Critical current density

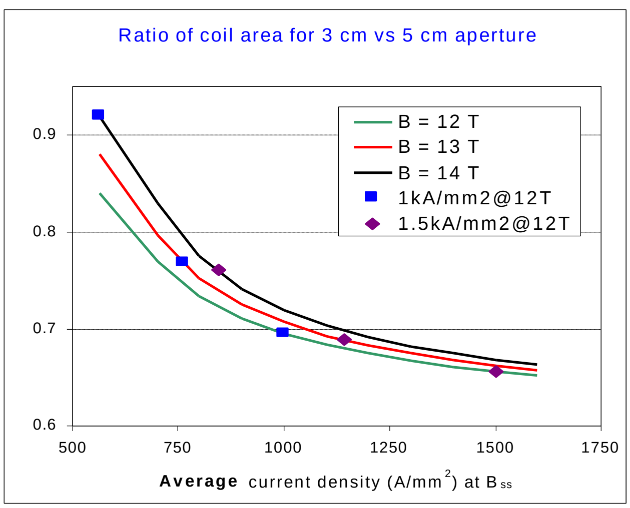
$$Jc(B,T,C0,e) := \frac{C(C0,e)}{\sqrt{B}}\cdot\left(1-\frac{B}{Bc2(T,e)}\right)^2\cdot\left[1-\left(\frac{T}{Tc0(e)}\right)^2\right]^2$$

(Summers, L, IEEE Trans. Mag 27-2)

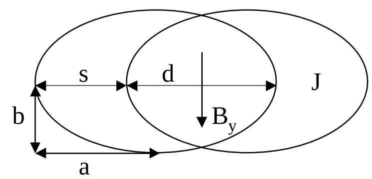
Jc(12T, 4.2K) = 2 - 3 kA



Choice of design parameters: conductor efficiency



Based on intersecting ellipses model



$$By = -\frac{m_0 Jsb}{a+b}$$

$$s(J,d,B) := \frac{-2\cdot d\cdot B}{B + mu0\cdot J\cdot d} \qquad a(J,d,B) := \frac{s(J,d,B)+d}{2} \qquad b(J,d,B) := \frac{d}{2}\cdot 1.1$$

$$Aoq(J,d,B) := a(J,d,B)\cdot b(J,d,B)\cdot\left(\frac{pi}{4} - \frac{1}{2}\cdot\frac{s(J,d,B)}{2\cdot a(J,d,B)}\cdot\sqrt{1-\frac{s(J,d,B)^2}{4\cdot a(J,d,B)^2}} - \frac{1}{2}\cdot asin\left(\frac{s(J,d,B)}{2\cdot a(J,d,B)}\right)\right)$$

$$Ahc(J,d,B) := \frac{pi\cdot a(J,d,B)\cdot b(J,d,B) - Aap(J,d,B)}{2}$$

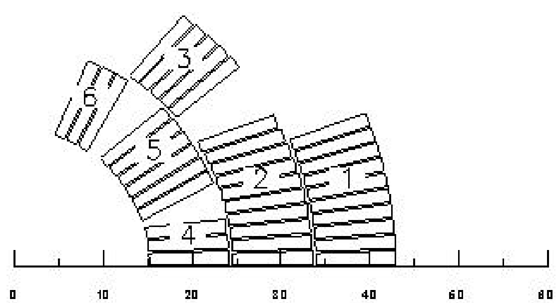
Design parameters

Coil aperture	:	30 mm
Coil width	:	27 mm
Coil layout	:	shell/block
No. of layers	:	3
Maximum field	:	12 T (Jc(12T, 4.2K)=2 kA/mm^2)
		13 T (Jc(12T, 4.2K)=3 kA/mm^2)
Geom. Harmonics	:	< 10^{-4} @ 1cm
Stress (Lorentz)	:	< 100 MPa

Shell type design: cable parameters

Strand diameter	mm	0.75
Cu/Sc ratio		1:1
No. of strands		24
Area of superconductor	mm^2	5.301
Cable width (bare)	mm	9.0
Cable mid-thickness (bare)	mm	1.35
Keystone angle	deg	1.8
Transposition length	mm	120
Compaction (area)	%	88.3
Compaction (inner edge)	%	80
Compaction (outer edge)	%	100
Radial insulation	mm	0.150
Azimuthal insulation	mm	0.120

Shell-type design: coil cross-section



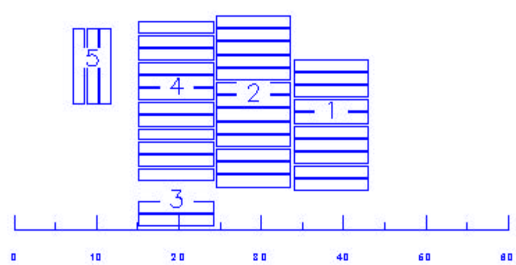
- 3 layer, 6 block design

- Optimized with ROXIE

Block type design: cable parameters

Strand diameter	mm	0.75
Cu/Sc ratio		1:1
No. of strands		24
Area of superconductor	mm^2	5.301
Cable width (bare)	mm	9.0
Cable mid-thickness (bare)	mm	1.35
Keystone angle	deg	0.0
Transposition length	mm	120
Compaction (area)	%	88.3
Compaction (inner edge)	%	90
Compaction (outer edge)	%	90
Radial insulation	mm	0.150
Azimuthal insulation	mm	0.120

Block-type design: coil cross-section

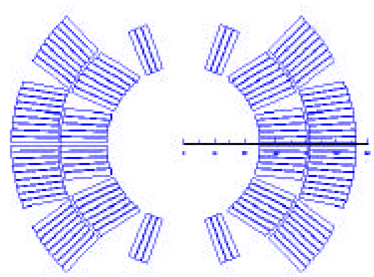


- 3 layer, 6 block design

- Optimized with ROXIE

50 mm bore, 2 layer shell type dipole design

- FNAL/LBL/KEK collaboration
- Cross section from FNAL TD-98-039
- Optimization work still underway (last update Oct 30)



Short sample performance/conductor efficiency

Parameter	Unit	Shell	Block	50 mm
SC area (1 quadrant)	mm^2	196	212	398
$Jc(12T, 4.2K) = 2\ kA/mm^2$				
I_{ss}	kA	10.1	10.1	18.0
$B^{(0)}_{ss}$	T	11.9	12.0	12.9
$B^{(max)}$ (layer 1)	T	12.2	12.2	13.2
$B^{(max)}$ (layer 3)	T	6.2	5.3	
$Jc(12T, 4.2K) = 3\ kA/mm^2$				
I_{ss}	kA	11.0	11.1	19.4
$B^{(0)}_{ss}$	T	13.0	13.1	13.9
$B^{(max)}$ (layer 1)	T	13.3	13.3	14.2
$B^{(max)}$ (layer 3)	T	6.8	5.8	

Energy and forces

Parameter	Unit	Shell	Block	50 mm
Operating current	kA	10.2	10.1	16.7
Stored energy	MJ/m	0.35	0.41	0.73
Inductance	mH/m	6.7	8.0	5.2
$-\Sigma F_y$ (1 quadrant)	MN/m	0.9	0.8	1.2
ΣF_x (1 quadrant)	MN/m	2.0	2.3	3.1
Stress (Φ/y, 1^{st} layer)	MPa	86	28	100
Stress (Φ/y, 2^{nd} layer)	MPa	84	36	75

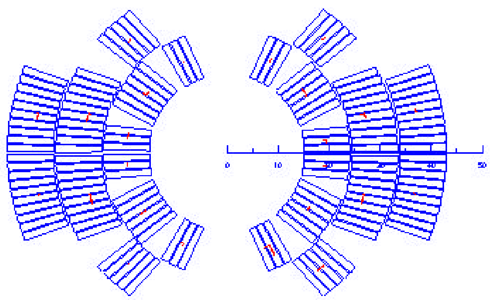
Geometric harmonics

10^{-4} @ 1cm

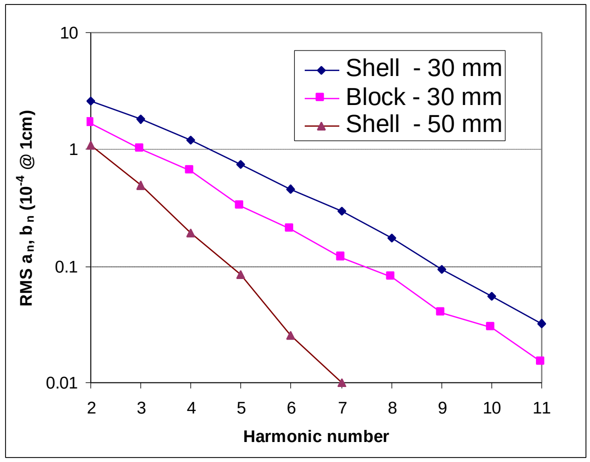
Component	Shell	Block	50 mm
b_3	0.1	-0.1	0.0
b_5	0.3	0.3	-0.1
b_7	0.7	0.6	0.0
b_9	0.6	-0.8	0.1
b_{11}	2.9	1.2	0.0
b_{13}	-0.5	0.2	0.0

Random errors

Random block displacement simulation using ROXIE
Shell: +/- 50 μm radial/azimuthal displacements
Block: +/- 50 μm horizontal/vertical displacements

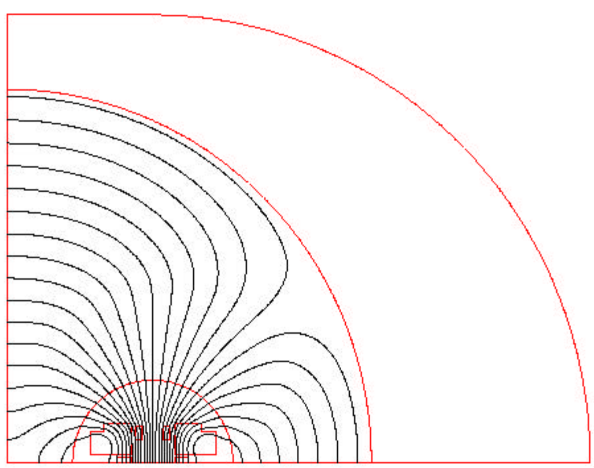


Random errors

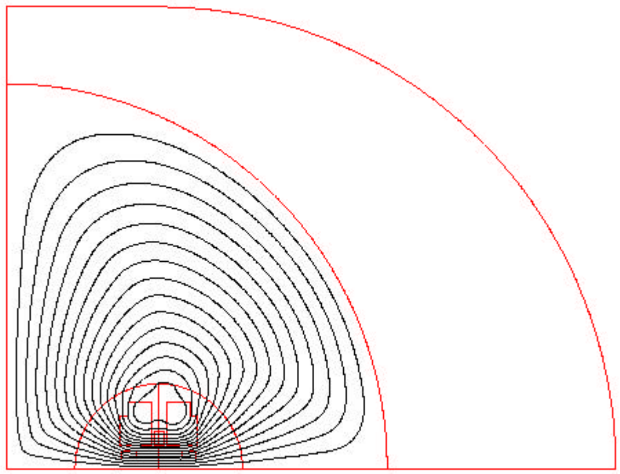


- No longitudinal averaging
- Magnetic measurements?

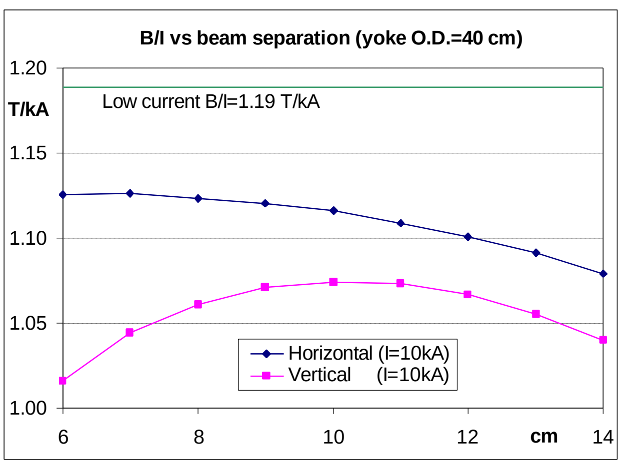
Horizontal two-in-one layout



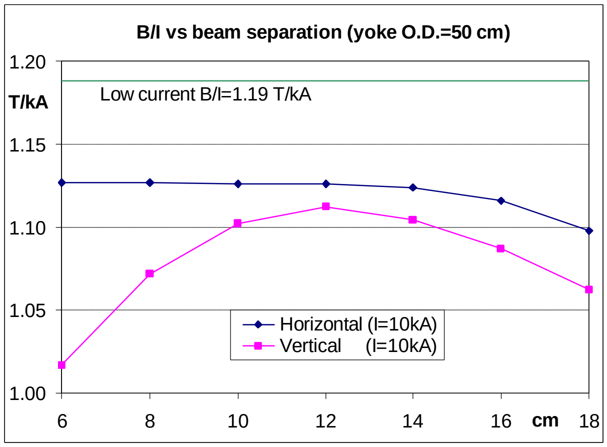
Vertical two-in-one layout



Transfer function for 40 cm yoke diameter



Transfer function for 50 cm yoke diameter



Next steps

- Field quality: further optimize geometric harmonics, evaluate magnetic measurement accuracy.

- End field quality (in particular for block type design).

- Mechanical parameters for conductor groups in the end regions (for shell type design).

Conclusions

- 30 mm bore dipole with 12-13 T design field using Nb3Sn conductor at 4.2 K allows substantial savings in superconductor wrt 50 mm bore magnet with same design parameters.
- For these design parameters, shell and block design are substantially equivalent in terms of conductor efficiency and field quality.
- Vertical arrangement of the two apertures requires 50% larger yoke radius wrt horizontal arrangement in order to achieve same transfer function.